

## Sensitivity of Nuclear Transition Frequencies to Temporal Variations in the Fine Structure Constant ( $\alpha$ -dot)

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There exist in nature a few long-lived nuclear states (isomers) with very low (eV) excitation energies. The best-known example is the 7.6 eV isomer of  $^{229}\text{Th}$ , which is estimated to have a lifetime of about 5 hours for decay to the ground state. The combination of the low energy and narrow width for the isomer makes this transition a candidate for laser-based investigations and possibly a sensitive probe for any temporal variation in the fine-structure constant  $\alpha = e^2/\hbar c$ .

Some evidence for a temporal variation of the fine structure constant has been reported from an analysis of quasar absorption spectra that suggests  $\dot{\alpha}/\alpha \sim 7.2 \times 10^{-16}/\text{year}$ . Laboratory searches for  $\dot{\alpha}/\alpha$  have concentrated on measurements of temporal changes in transition frequencies between nearly degenerate atomic levels. More recently it has been suggested that the nearly degenerate nuclear levels in  $^{229}\text{Th}$  may provide several orders of magnitude more sensitivity to  $\dot{\alpha}/\alpha$  than do atomic levels (Fig. 1). In the present research we examined the underlying physics that determines the sensitivity of nuclear transition frequencies to  $\dot{\alpha}/\alpha$ .

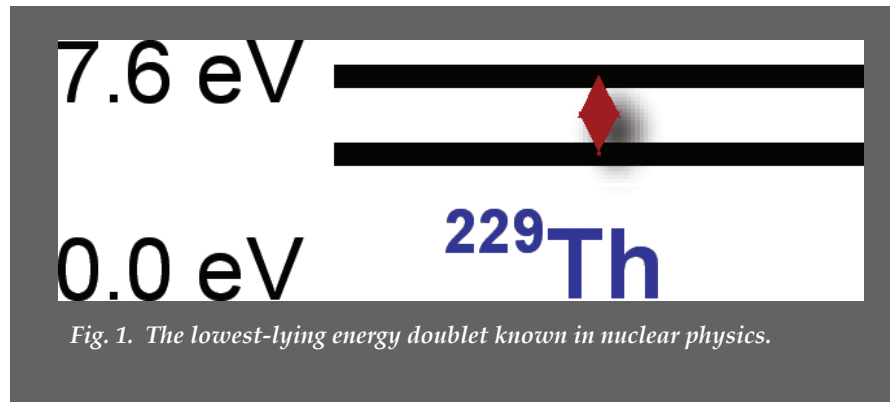
The energy of a transition ( $\omega$ ) between the ground state and an excited state of any nucleus is determined by the difference of matrix elements of the nuclear Hamiltonian, and the sensitivity to  $\alpha$  enters through the Coulomb interaction between nucleons in the nucleus. Invoking an extension of the Feynman-Hellmann theorem, we found the simple result that a temporal variation of the transition frequency  $\omega^*$  depends on  $\dot{\alpha}/\alpha$  as:

$$\omega^* = (\langle f | V_C | f \rangle - \langle g.s. | V_C | g.s. \rangle) \dot{\alpha}/\alpha$$

where  $\langle f | V_C | f \rangle$  and  $\langle g.s. | V_C | g.s. \rangle$  are the isomeric-state and ground-state Coulomb energies. Thus the variation in the transition frequency due to the fine-structure constant is driven solely by the Coulomb-energy difference of the two states.

The low-lying states in  $^{229}\text{Th}$  are normally described in terms of the nuclear Nilsson model. In this picture the states are modeled as an active neutron in a deformed potential well. This model predicts that the Coulomb energies of the doublet are the same, and that they arise from the same deformed nuclear core. Thus  $(\langle f | V_C | f \rangle - \langle g.s. | V_C | g.s. \rangle) = 0$  and there is no sensitivity to  $\dot{\alpha}/\alpha$ . We also examined a more sophisticated model for  $^{229}\text{Th}$  that represents the first-order correction to the Nilsson model, namely the inclusion of the pairing interaction between neutrons. However, in this model the sensitivity to  $\dot{\alpha}/\alpha$  remained zero because the Coulomb deformation of the two states was unchanged.

We concluded that a large enhancement in the temporal change of the nuclear transition frequency due to a finite  $\dot{\alpha}/\alpha$  is difficult to realize in  $^{229}\text{Th}$ . The main issue is that the magnitude of the enhancement is determined by the difference of the Coulomb energies of the two states, and that the latter is constrained to be small because the two states differ mainly in their neutron (but not their proton) structure.



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